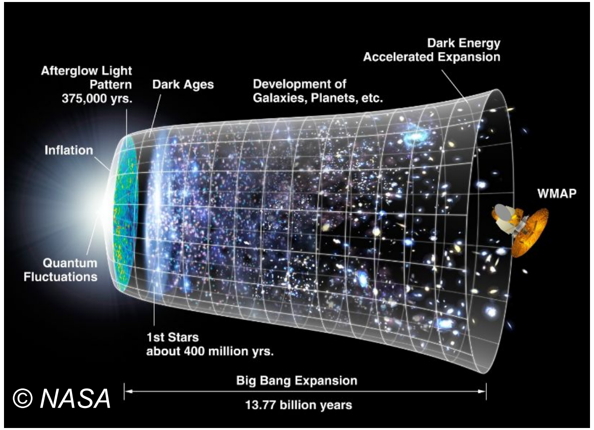
Galaxy formation and evolution

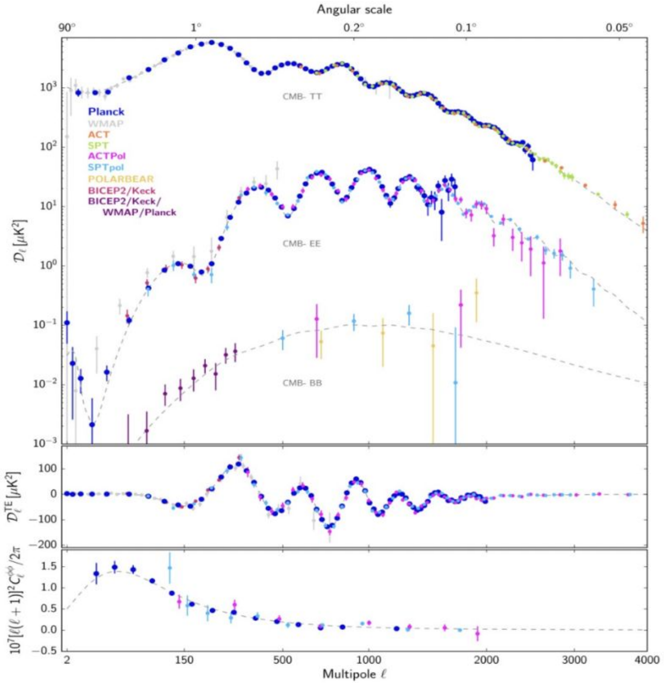
Gabriella De Lucia & Anna Gallazzi

The framework



An era of `precision cosmology', with an established standard model for structure formation.

that reproduces a wide range of observational results (galaxy power spectrum, Lyman alpha forest, SN, cosmic shear, baryon fractions in clusters …. CMB)

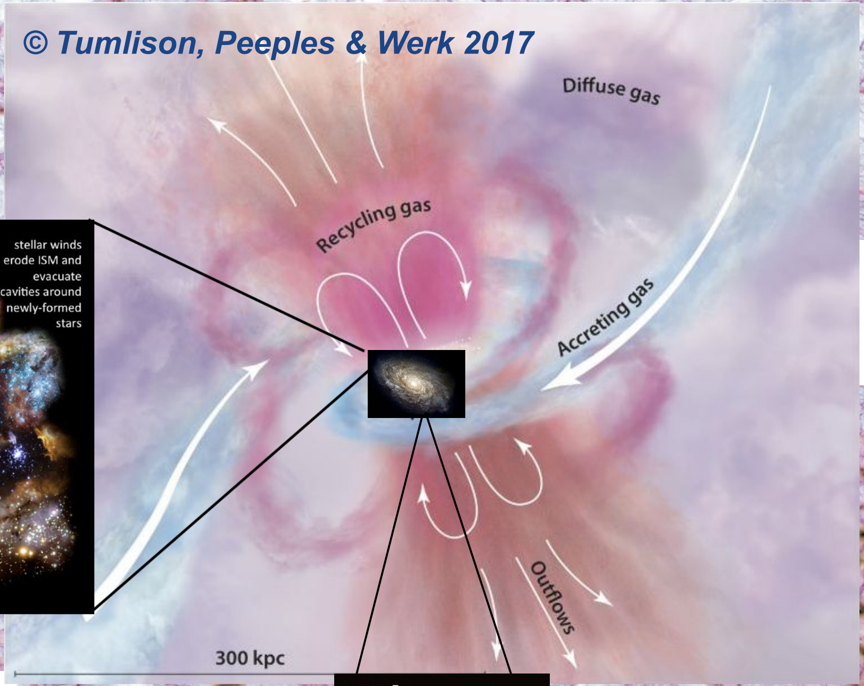


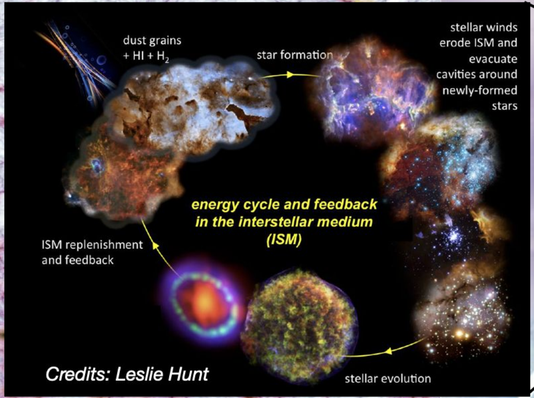
Basic assumption: galaxies form from the condensation of gas at the centre of dark matter haloes that assemble in a bottom-up fashion with larger haloes forming at later times.

See review by Meneghetti & Cardone

Planck Collaboration, 2020

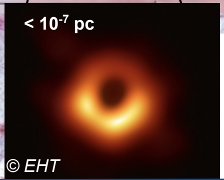
Galaxy ecosystems within an evolving cosmic web





Gas infall - new fuel/metal dilution
Gas stripping
Mergers/accretion

Star formation - gas consumption
Metal production and recycling
Stellar and SN feedback



AGN feedback
Gas heating
Outflows

Galaxy components

ISM

Ionized: Star formation, metallicity and nuclear activity

optical/NIR spectroscopy

Atomic and molecular: reservoir for SF; dynamics

Radio and submm

Stars

Physical properties: fossil record of past SFH and chemical enrichment

Morphology and dynamics: fossil tracers of past SF and assembly history

UV/optical/NIR imaging and spectroscopy

CGM

Reservoir of **multiphase gas** that represents an interface between IGM and ISM.

Quasar absorption line spectroscopy, down-the-barrel spectroscopy

Review by D'Odorico & Fontana

Dust

Star formation and metal recycling

UV/optical (absorption), IR, submm (emission)

Dark Matter

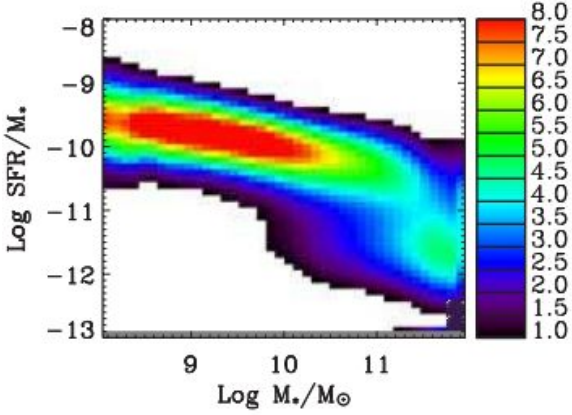
Total gravitational potential, `environment'

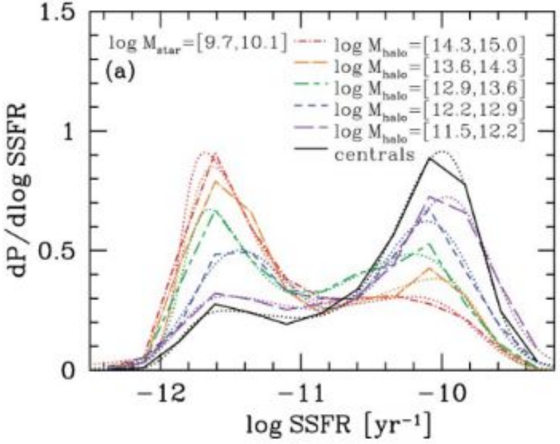
Gas and stellar dynamics, gravitational lensing

Broad expertise at INAF, taking advantage of major observational facilities and a broad range of theoretical tools.

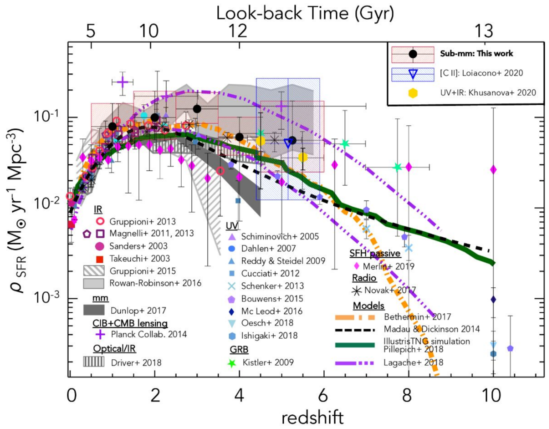
Observational facts

Brinchmann et al. 2004



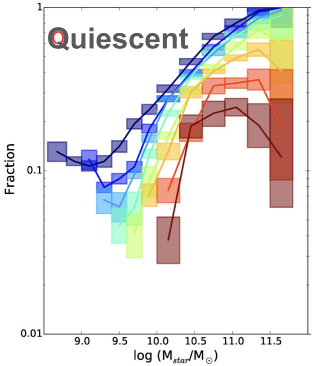


Wetzel et al. 2012

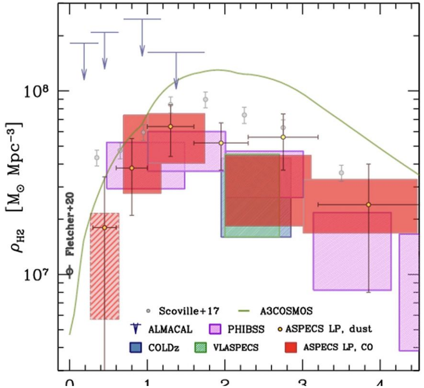


Gruppioni et al. 2020

The last 10-12 billion years of cosmic history are a critical period, from the emergence of the first massive evolved systems to the global decline of SF and the build-up of the passive populations, in the evolving LSS

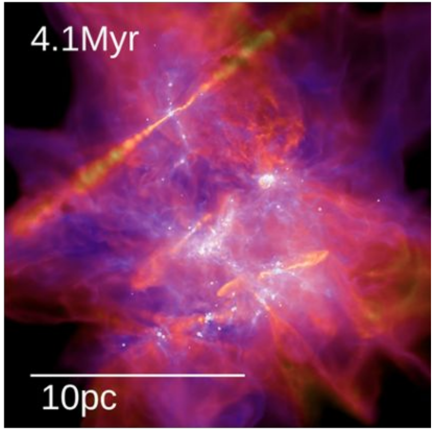


Martis et al. 2016



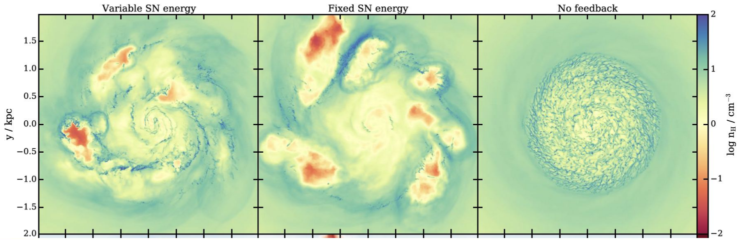
Decarli et al. 2020

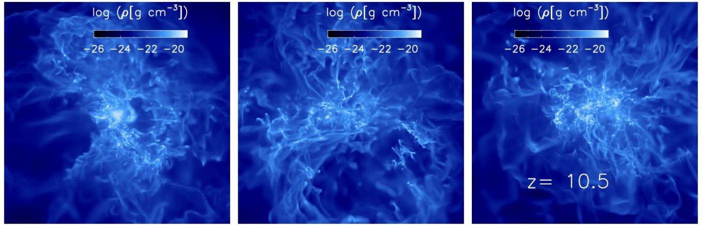
Theoretical developments



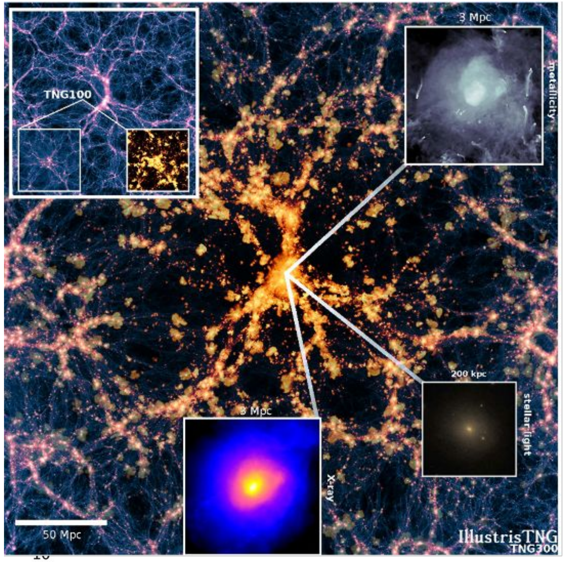
Grudic et al. 2021

Gutke et al. 2021



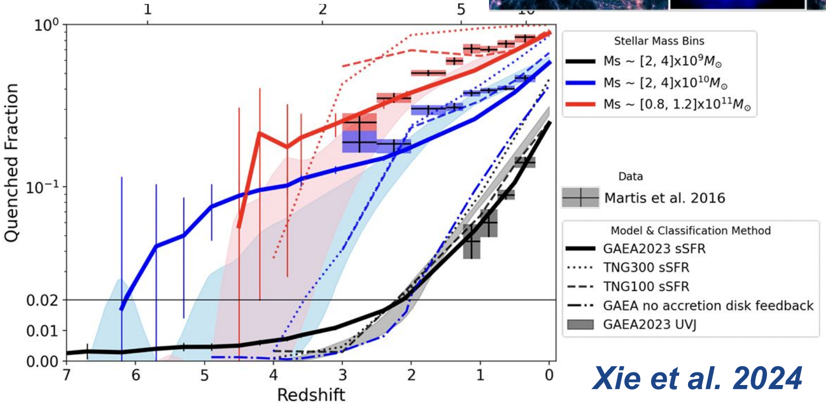


Calura et al. 2025



Illustris TNG

A range of tools incorporating ever more faithful descriptions of the various physical processes at play and that are key to both interpret data and for guiding the construction of new observational programmes.



Xie et al. 2024

The open questions

INAF Strategic Vision document (**2019** - subset of relevant questions):

- ➢ Origin and fate of galaxies, the galaxy stellar mass function and morphological differentiation
- ➢ Feedback processes among the different components of galaxies (stars, gas, dust) and AGN. Role of DM halos
- ➢ External and internal mechanisms (environment and relationship with the Cosmic Web) regulating the efficiency of star formation and the structural parameters of galaxies

2020 Decadal Survey Priority Area: Unveiling the Drivers of Galaxy Growth.

- ➢ How do gas, metals, and dust flow into, through, and out of galaxies?
- ➢ How do supermassive black holes form and how is their growth coupled to the evolution of their host galaxies?
- ➢ How do the histories of galaxies and their dark matter halos shape their observable properties?

Our view of the open questions today

INAF Strategic Vision document (**2019** - subset of relevant questions):

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2020 Decadal Survey Priority Area: Unveiling the Drivers of Galaxy Growth.

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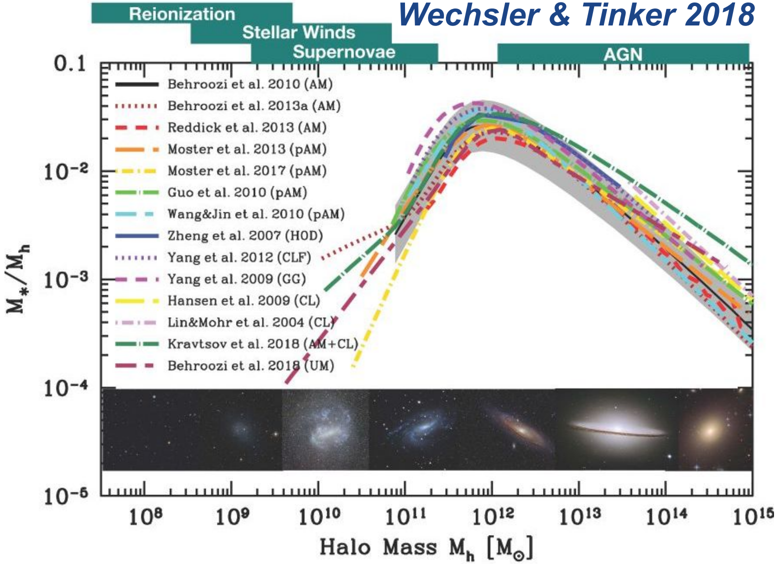
What are the drivers of galaxy growth?

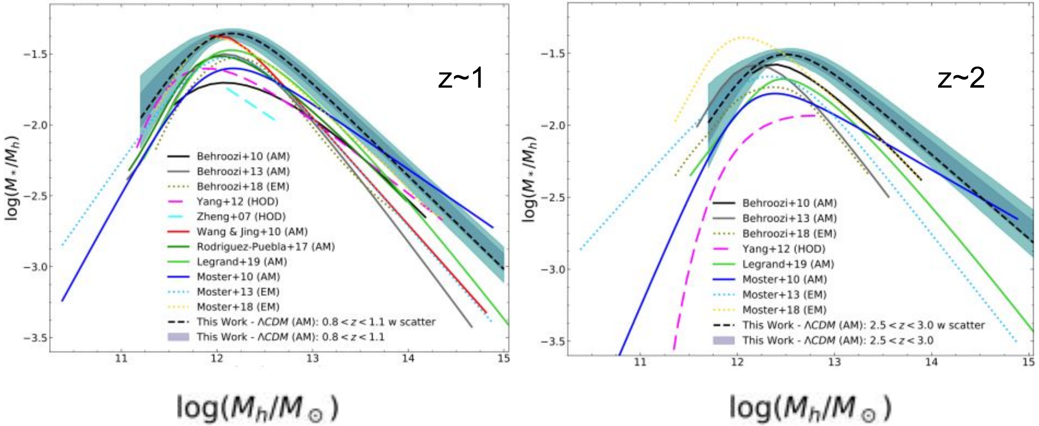
- ➢ ***How is the galaxy baryon cycle regulated by the assembly of dark matter haloes and large scale structure?***
- ➢ ***What are the physical processes that regulate the production and retention of metals within different baryonic components?***
- ➢ ***How did the first massive galaxies assemble and quench and to what extent can they rejuvenate at later times?***
- ➢ ***How does the growth of the LSS and cosmic web impact morphological and physical properties of galaxies?***

Galaxies and dark matter halos

Wechsler & Tinker 2018



Girelli et al. 2020

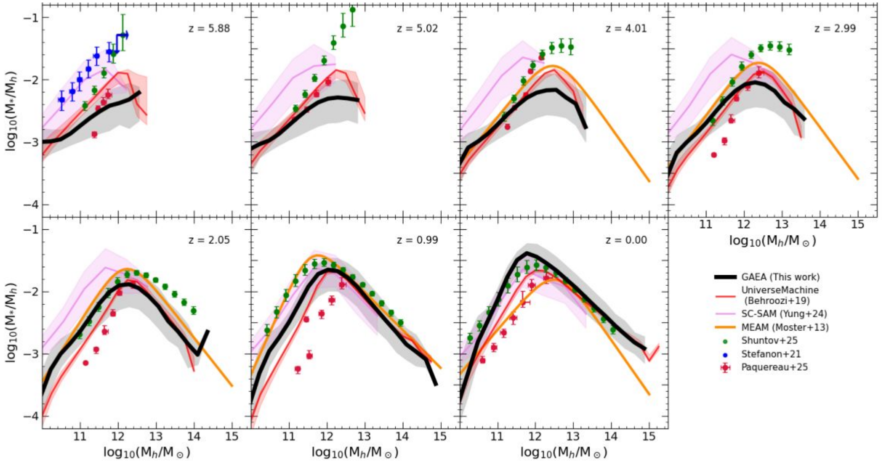


Mostly based on Abundance Matching techniques (parametrized - these can use additional info from clustering) + (at massive end) direct measurements at group/cluster scales (e.g. lensing, dynamics, ..).

Limits/caveats: scatter (uncertainties increases with increasing z) typically assumed to be log-normal, random and constant. Assembly bias?

Galaxies and dark matter halos - future

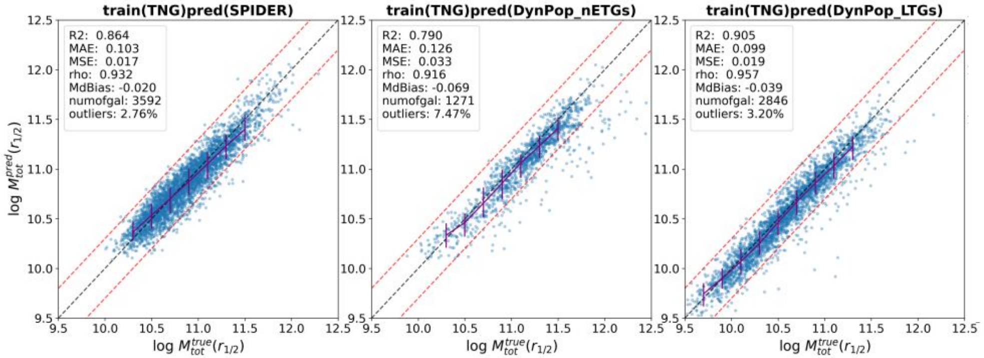
Cantarella et al. 2026



<u>Mapping of the high-redshift Universe</u> (JWST, ELTs…) to testing if SFE was significantly higher at early epochs.

Significant INAF involvement on both the observational and theoretical side.

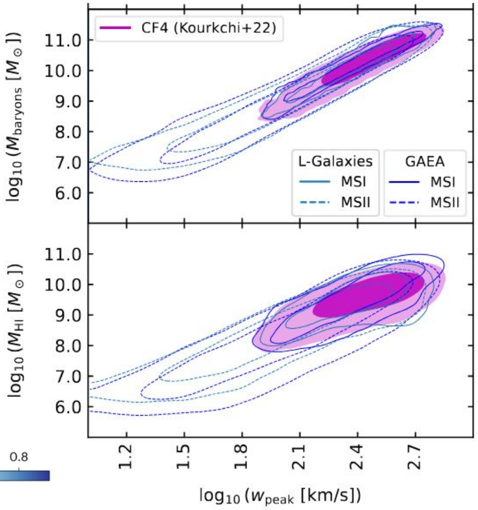
Wu et al. 2024

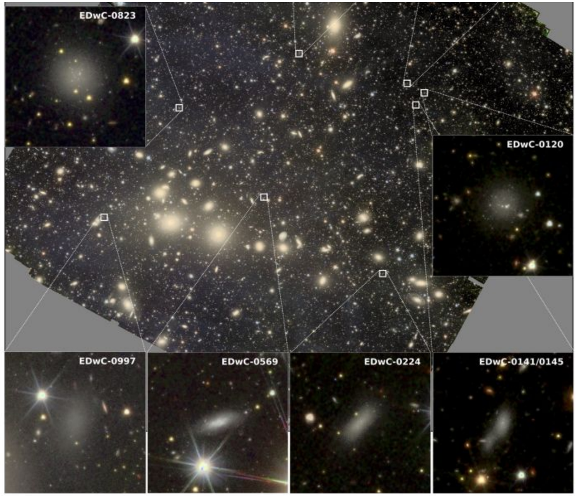


<u>Reduced bias in halo mass estimation</u> through lensing, clustering, SZ, large spectroscopic samples, kinematics … (Euclid, LSST, MOS,…). Significant improvements can come also through machine learning techniques.

Galaxies and dark matter halos - future

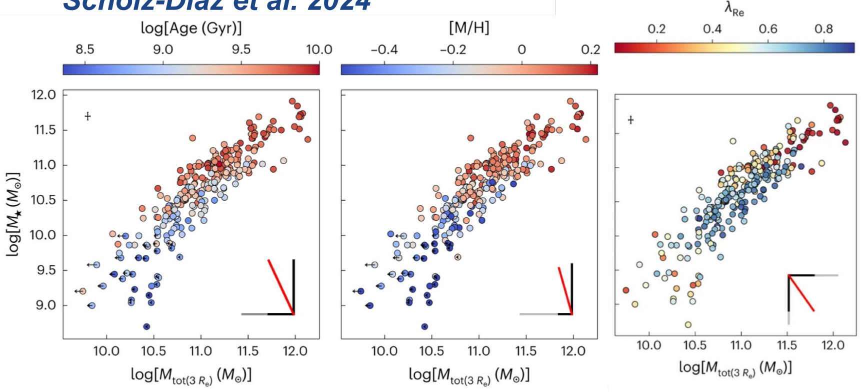
Mayor et al. in preparation





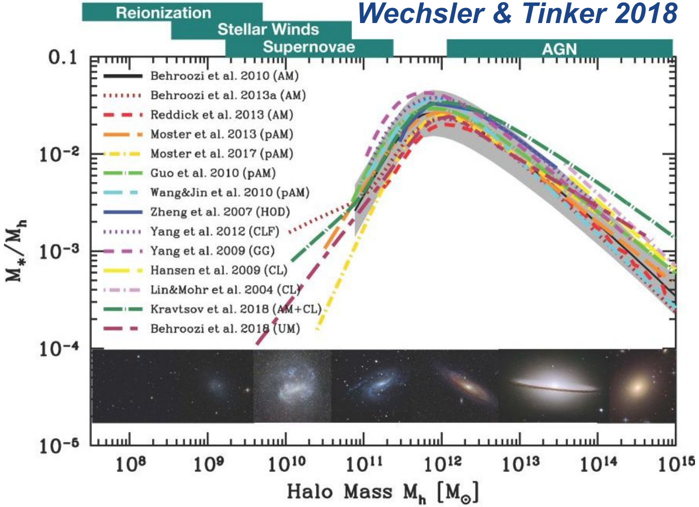
<u>Characterization and modeling of the scatter</u> better understanding of the secondary dependences (e.g. environment, gas content, angular momentum, galaxy physical properties)

Scholz-Diaz et al. 2024



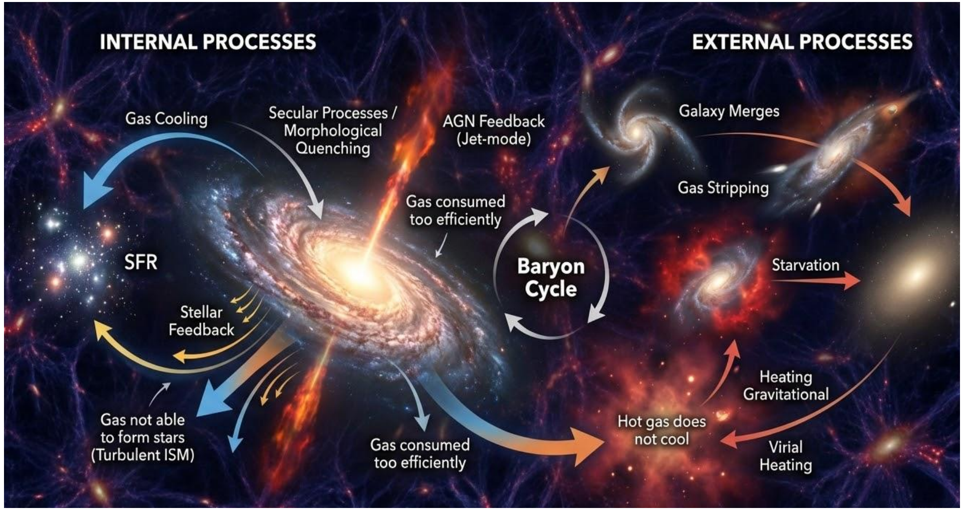
<u>Improved constraints on dwarf galaxies</u> (both numbers and properties) through galaxy-galaxy lensing, stellar halos, gas,… (Euclid, LSST, Roman, SKA, …)

Regulation and suppression of star formation



Wechsler & Tinker 2018

Different mechanisms regulate the efficiency of galaxy formation and quenching at different halo masses, which is related to the emergence of a bimodal population.



Imprint on:

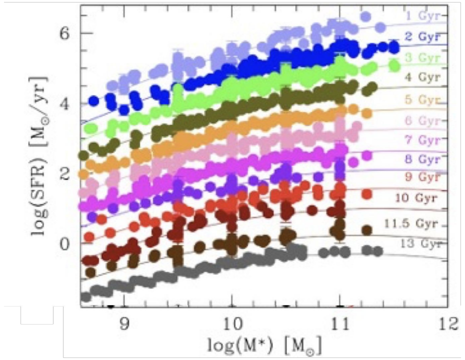
- ➢ Metals in the gaseous and stellar phase
- ➢ Gaseous content
- ➢ Environmental dependence

Review by Decarli & Valiante for AGN feedback

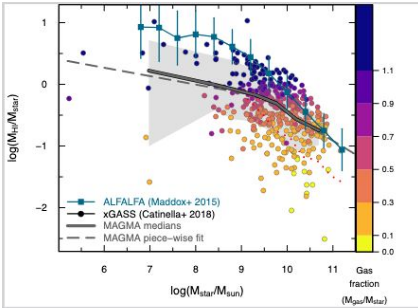
Fundamental scaling relations: star formation and gas

***ALMA** instrumental to trace molecular gas in distant galaxies*
***SKA and precursors** to trace HI out to cosmic noon*

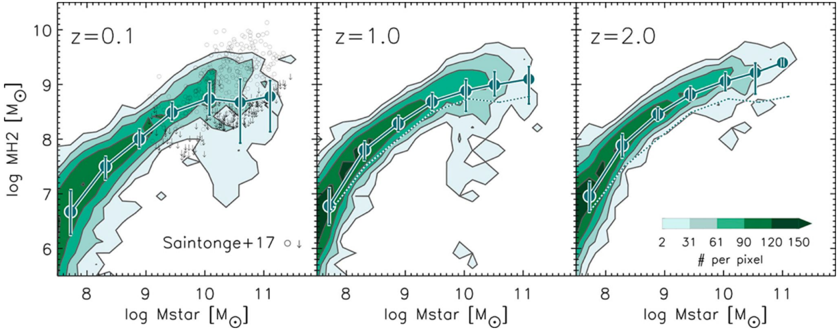
Popesso et al. 2023



Hunt et al. 2020

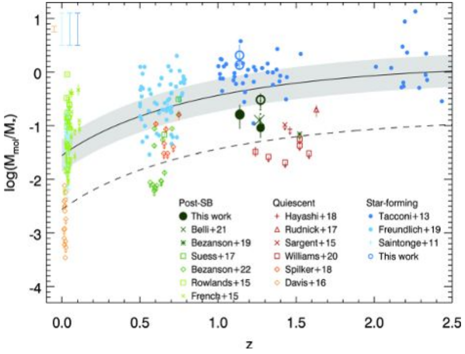


Ragone-Figueroa et al 2024

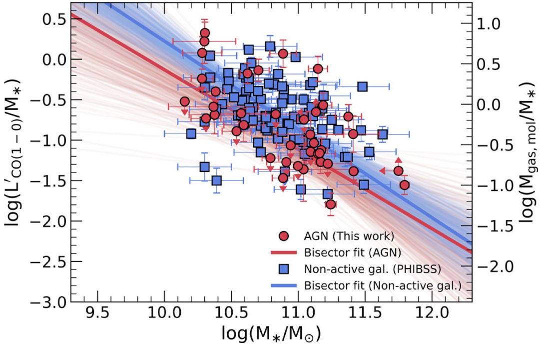


What makes galaxies deviate above or below the MS?
Available (cold) gas reservoir VS depletion timescales
Interactions VS secular processes
What causes the MS turnover? Bulge growth VS rejuvenation (Mancini+19)

Zanella et al. 2023

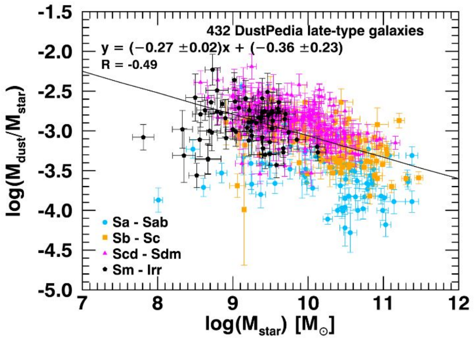


Bertola et al. 2024



Fundamental scaling relations: dust

Casasola+20 (DustPedia), Herschel

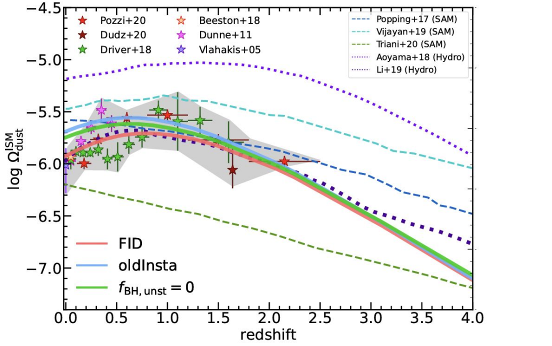


Minor but important ISM component in regulating cooling and molecular gas formation, and in tracing chemical enrichment

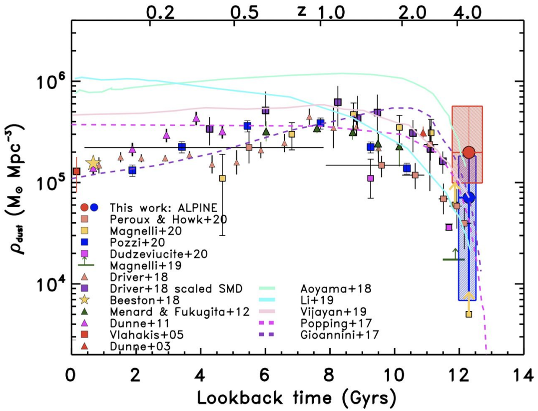
***ALMA** instrumental to trace dust at high z*

***JWST** enables measures of dust attenuation and PAH features in distant galaxies*

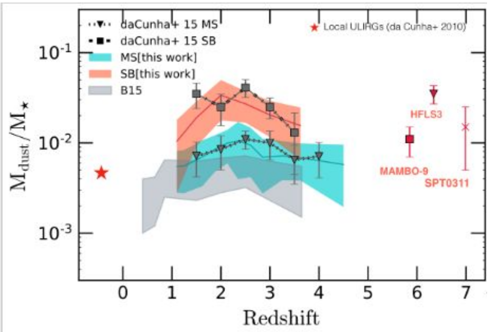
Parente et al. 2022 - L-Galaxies +dust



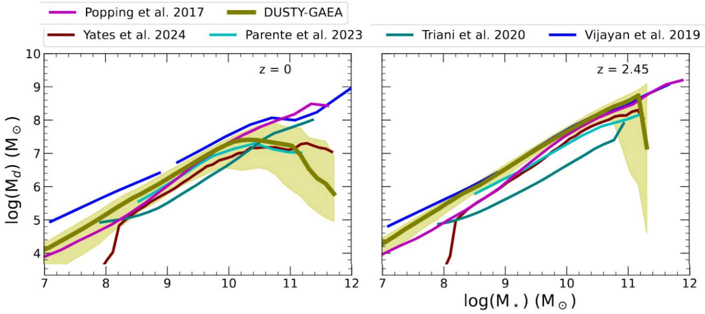
Pozzi et al. 2021 - ALPINE-ALMA



Donevski et al 2020, ALMA

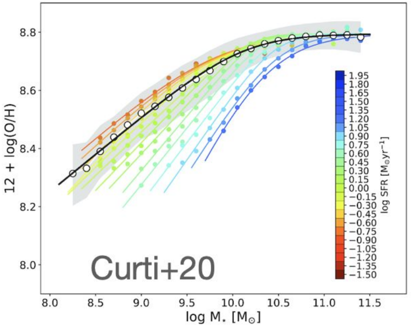


Osman et al. 2026 - DUSTY-GAEA

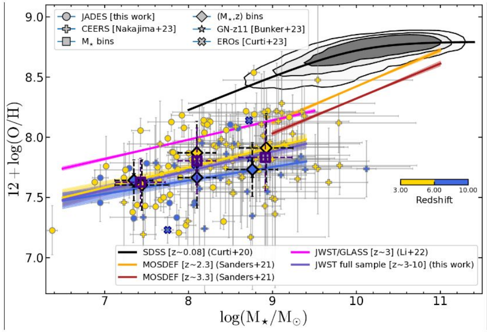


Fundamental scaling relations: ISM chemical enrichment

Equilibrium between star formation, inflows of pristine gas and metal-rich outflows

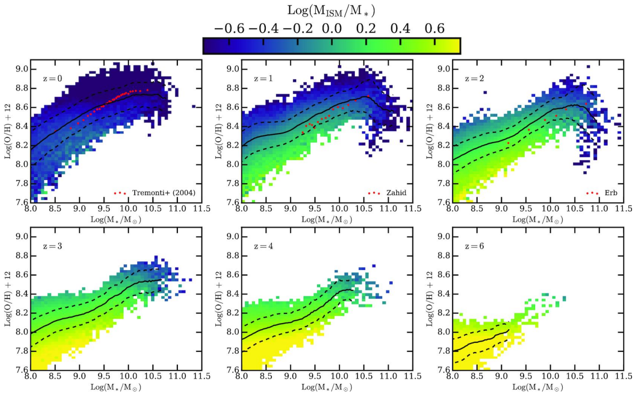


Curti et al 24 (JADES)

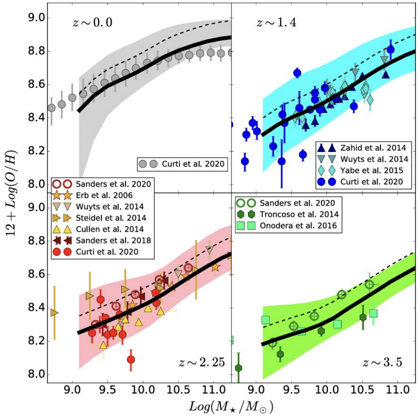


Constraints for SAM and hydro-simulations
Gas fraction/retention versus SFR as driver of metal recycling equilibrium?

Torrey et al 2019, IllustrisTNG



Fontanot et al 2021, GAEA



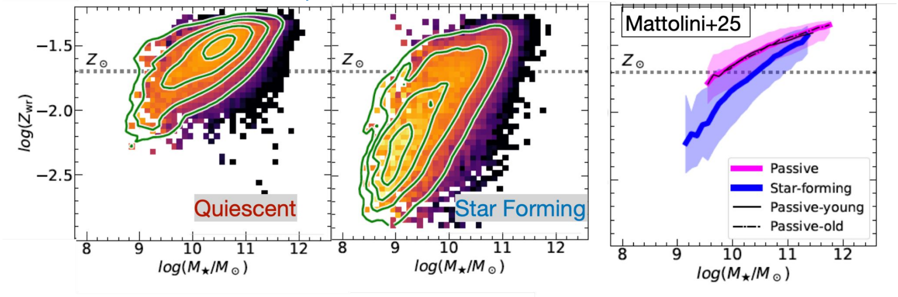
MOONS will provide unprecedented statistics out to cosmic noon
JWST is allowing faint auroral line detections and robust gas metallicity estimates out to z~9
INAF researchers involved/leading JWST projects

Fundamental scaling relations: stellar chemical enrichment

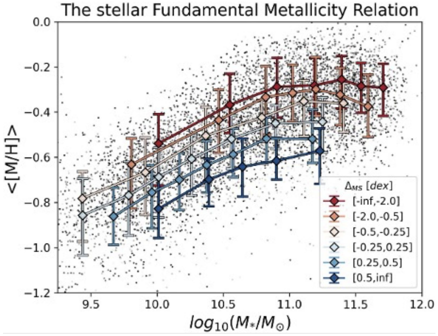
Fossil record of integrated histories of star formation, metal recycling and mass assembly

Different chemical enrichment for Q and SF and stellar FMR ?

Mattolini et al 2025, SDSS



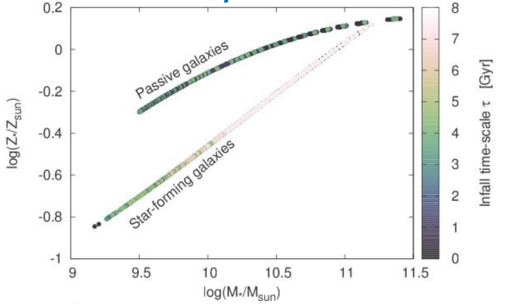
Looser et al 2023, MaNGA



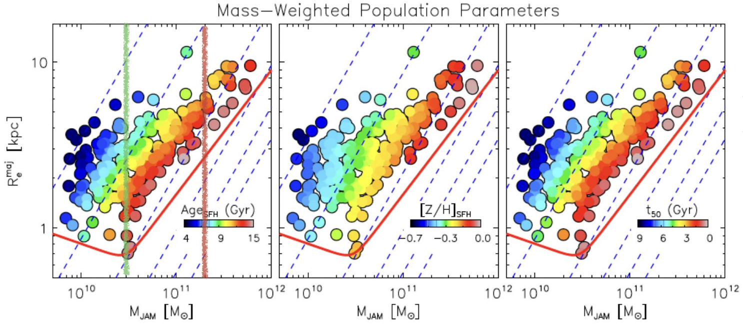
Chemical evolution models

Efficiency of gas infall, star formation suppression mechanisms, outflows, or structural differences

Spitoni et al 2017



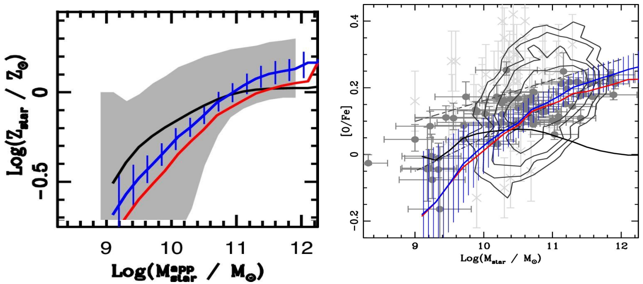
McDermid et al 2015, ATLAS3D



The age and chemical composition of stellar populations to an ***earlier and faster formation for more massive galaxies and for more compact galaxies***

Constraints on quenching mechanisms, IMF and implications for physical interpretation of abundance ratios

Fontanot et al 2017

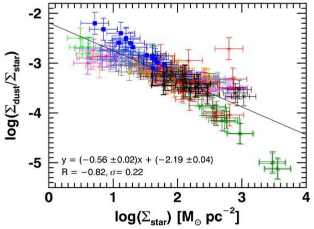


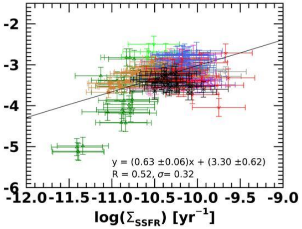
Global or local drivers of star formation and metal enrichment?

Global scaling relations have a spatially-resolved counterpart – the breakthrough of optical/NIR Integral Field Spectroscopy

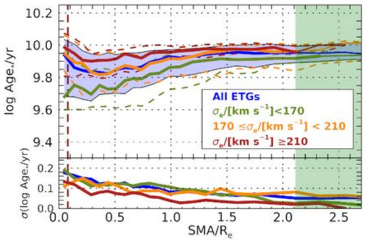
Local conditions (surface mass density) modulated by total potential well and environment
Imprint of accretion and assembly history on gradients in physical properties

Casasola et al 2022, DustPedia

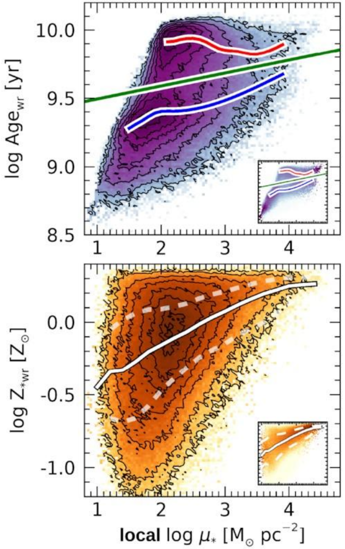




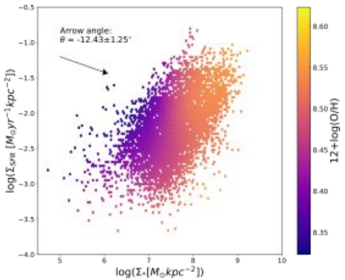
Zibetti et al 2020, ETG



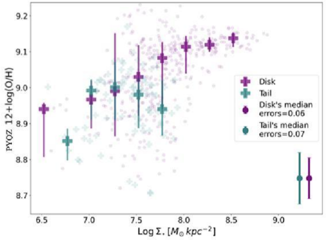
Zibetti & Gallazzi 2022, CALIFA all



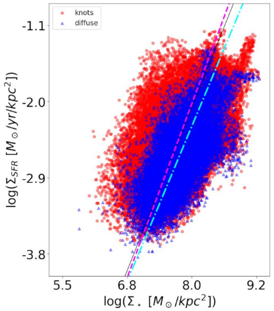
Koller et al 2024, MAGPI

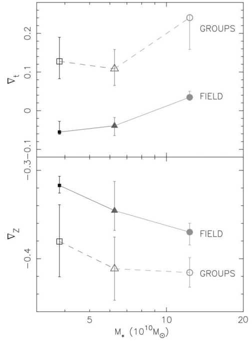


Khoram et al 2024, GASP-MUSE



Vulcani et al 2019





La Barbera et al 2011

See talk by Marasco & Belfiore for baryon cycle

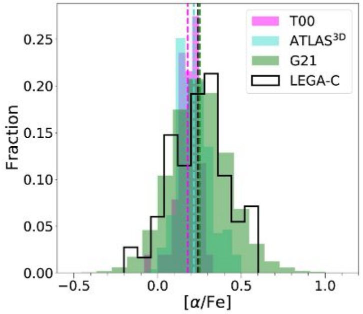
Stellar abundance measurements since cosmic noon

Currently we can trace stellar metallicity and abundance ratios for the general population up to z<1 (**LEGA-C**) and for star-forming galaxies from UV up to z~3 (**VANDELS**)

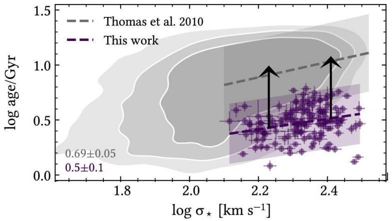
Bridging LEGA-C and SDSS with larger samples and deeper spectroscopy from WEAVE and 4MOST-StePS
Extend to z<2 with MOONS

Strong INAF involvement and PI-ship

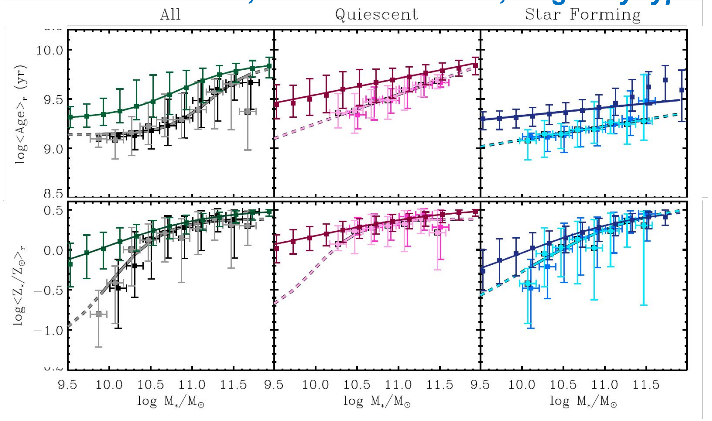
Bevacqua et al 2023, LEGA-C, passive



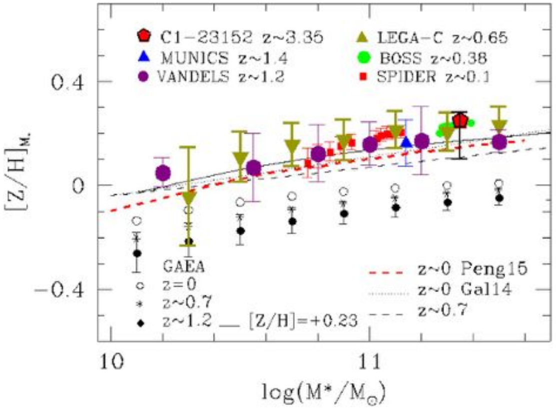
Borghi et al 2022, LEGA-C, passive



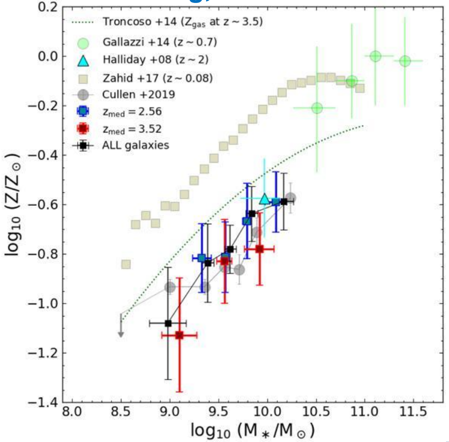
Gallazzi et al 2026, LEGA-C and SDSS, all galaxy types



Saracco et al 2023, VANDELS, passive



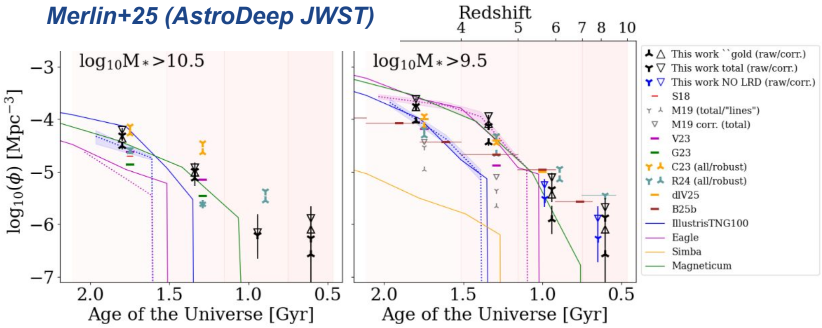
Calabro' et al 2021, VANDELS, Star-forming, UV lines



Emergence of massive evolved galaxies beyond cosmic noon

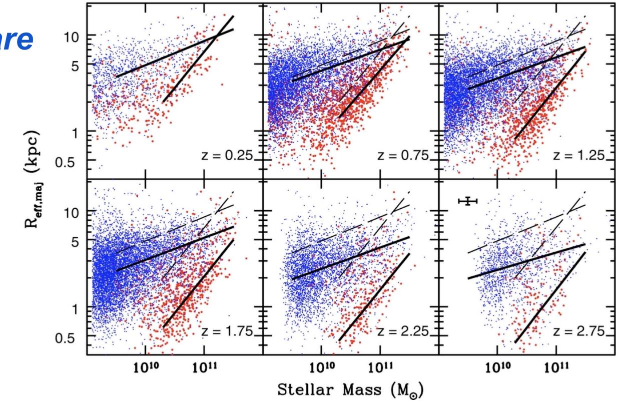
JWST is pushing to higher z and to higher number densities the discovery of massive evolved (passive) galaxies

Merlin+25 (AstroDeep JWST)



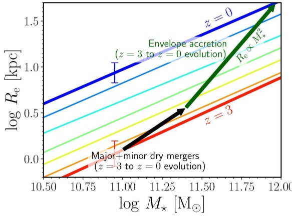
van der Wel et al 2014

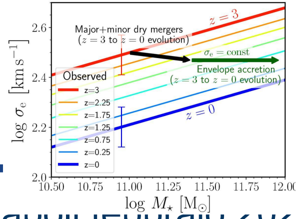
Passive galaxies are significantly more compact at high z



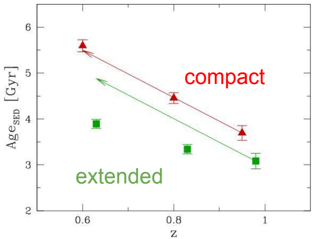
Evolution in size and dynamics, and stellar population trends constrain balance between continuous population quenching and individual growth through (minor) merging

Nipoti 2025

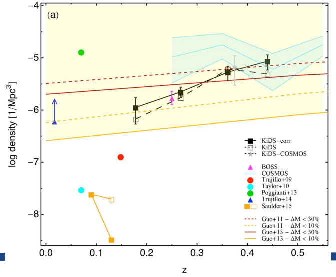




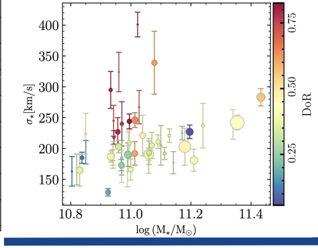
Gargiulo et al 2017



Tortora et al 2018, KiDS



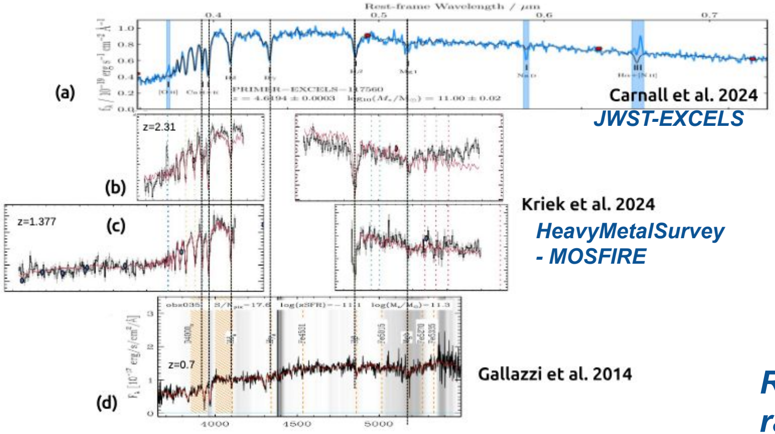
Spiniello et al 2023, INSPIRE



Ultra compact galaxies at intermediate z: *Relic galaxies not undergoing minor merging?*

Emergence of massive evolved galaxies beyond cosmic noon

Trace their evolving properties in a demographic sense with current spectroscopic facilities



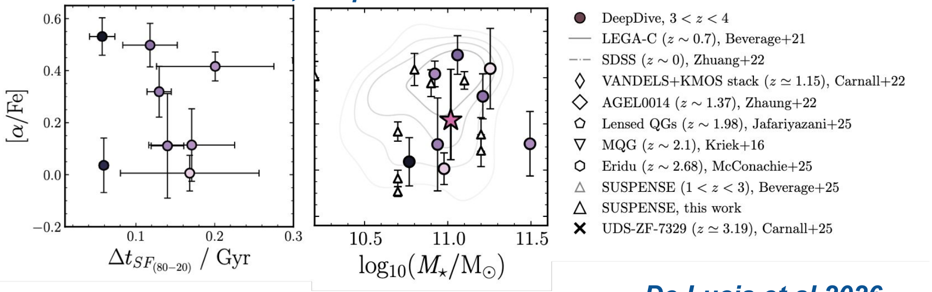
JWST-EXCELS

Kriek et al. 2024

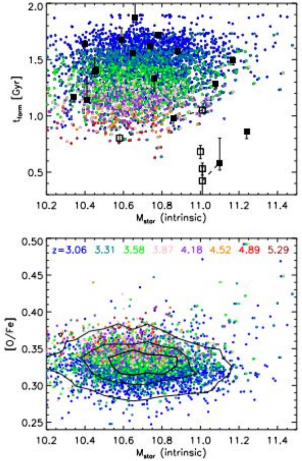
HeavyMetalSurvey - MOSFIRE

Gallazzi et al. 2014

Hamdouche et al 2026, DeepDive 3<z<4

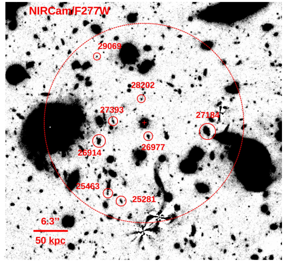


De Lucia et al 2026



Rapidly formed and quenched, α-enhanced - but range of formation redshift and α/Fe reproduced in models

- ***How robust are stellar masses, metal abundances and abundance ratio estimates of young high-z galaxies?***
- ***What α-enhancement tells us about star formation timescale?***
- ***How quiescent are "quiescent" galaxies? For how long do they remain quiescent?***
- ***What is the environment of massive evolved galaxies at z>3?***



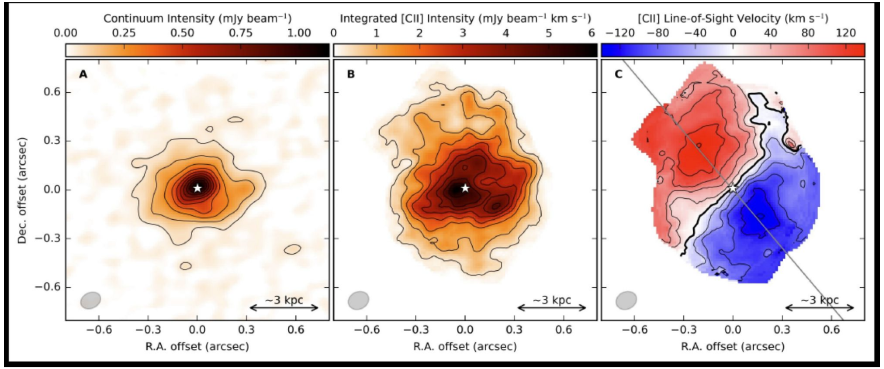
Bevacqua et al 2026, neutral gas inflow in a z=2.6 massive Q galaxy

See talk by La Barbera for SPS model challenges

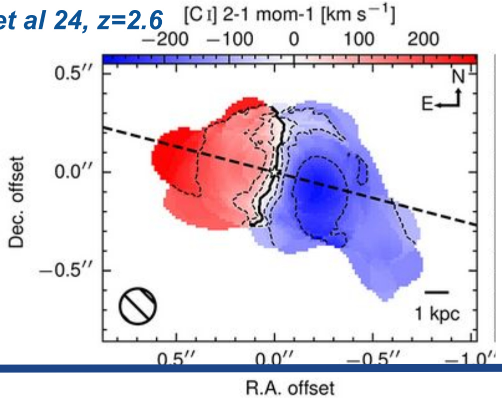
Emergence of massive evolved galaxies beyond cosmic noon

ALMA reveals massive regular rotating disks and bulge component at cosmic noon and beyond

Lelli et al 2021, z=4.75



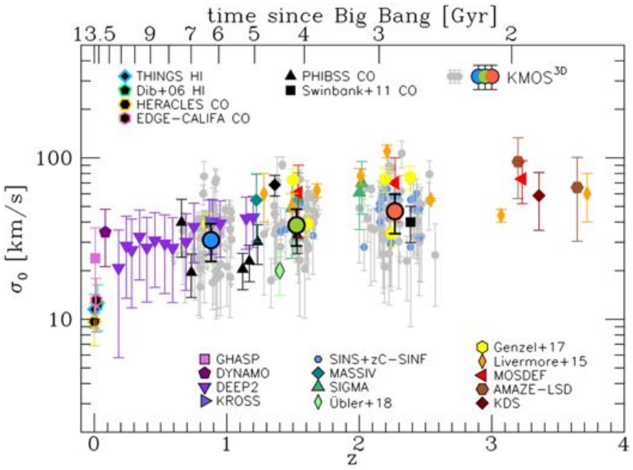
Lin et al 24, z=2.6



TRICEPS: *Gas and stellar tracers (**JWST+ALMA**) of dynamics to constrain total mass and DM content*

Contrast with turbulent disks found with ionized gas kinematics

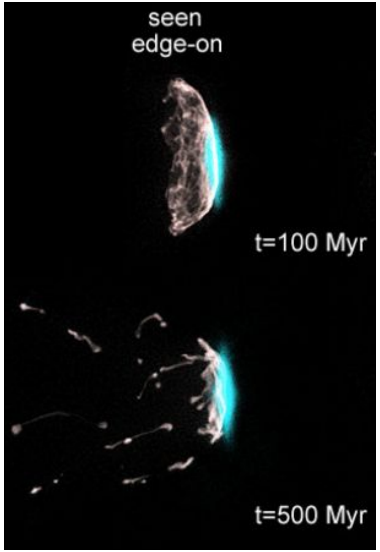
Ubler et al 2019, KMOS3D



Galaxy evolution and environment

<u>Nurture</u>: interaction with other group/cluster members and/or halo potential; interactions with the hot gas that permeates massive galaxy systems.

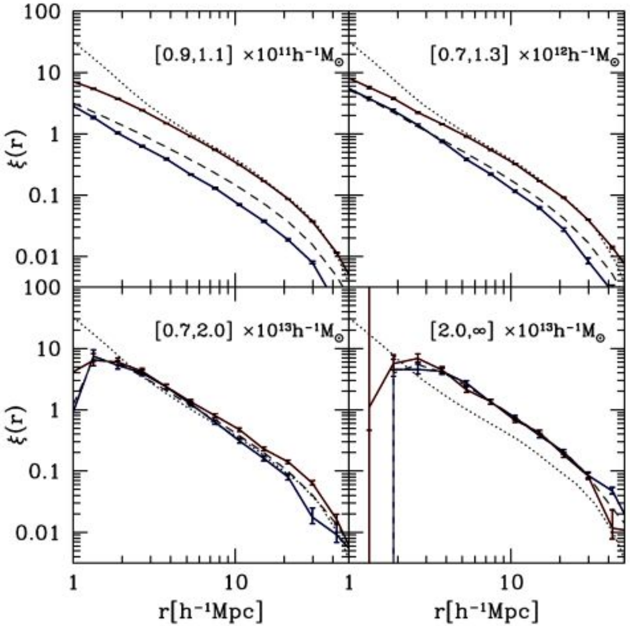
What is their relative role? And (how) can we disentangle their effect?



Kronberger et al. 2008

Moore et al. 1996

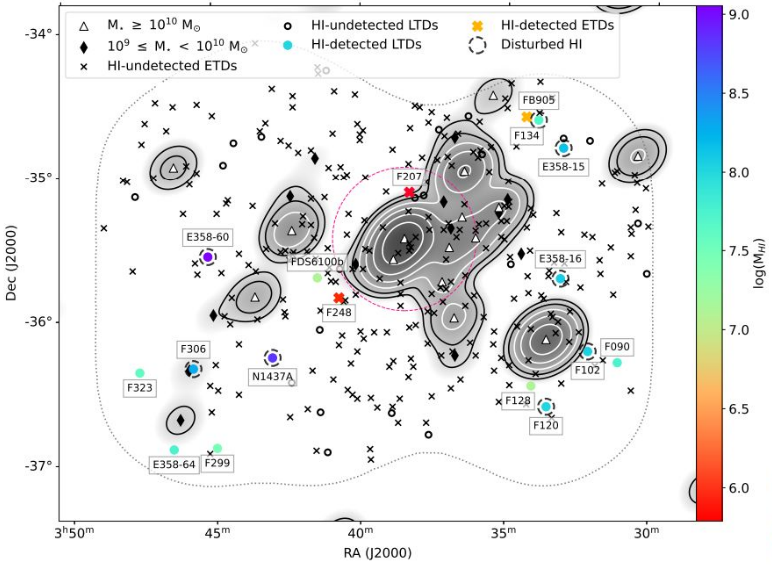
Gao et al. 2005



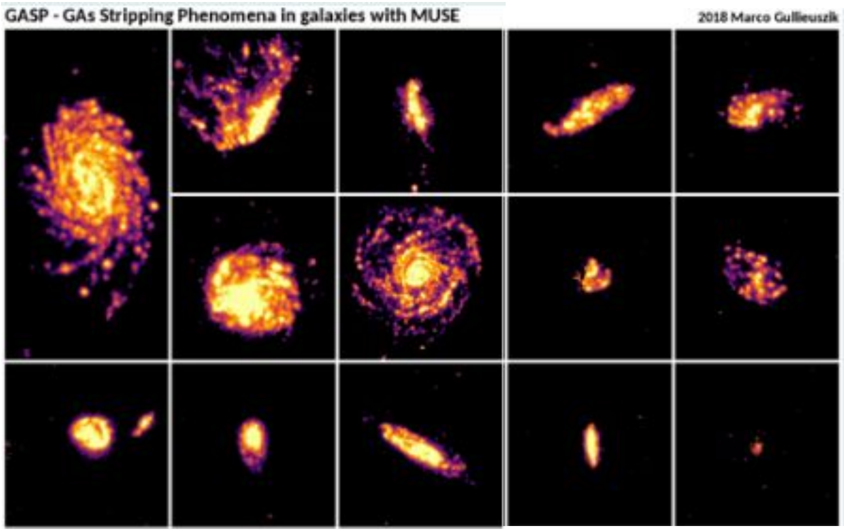
<u>Nature</u>: halo properties (spin, concentration, shape…) show environmental dependencies, which is bound to leave an imprint on galaxy properties.

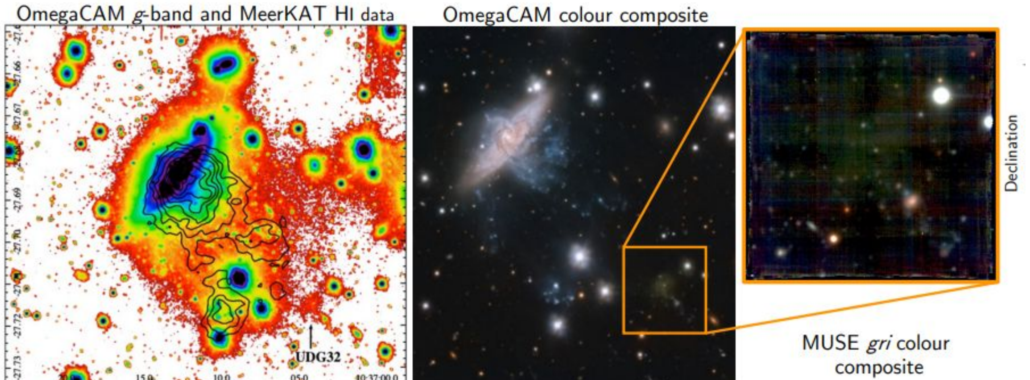
Environment - clusters

Kleiner et al. 2023 - MeerKAT Fornax Survey



Multi-wavelength characterization of the galaxy cluster population in the local Universe.

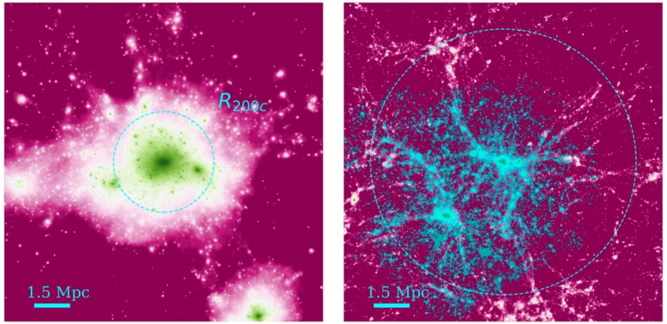




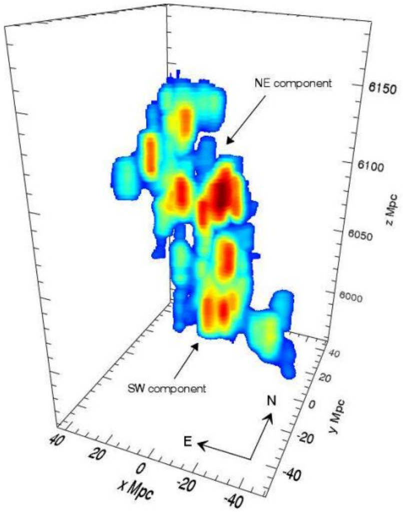
Hartke et al. 2025 (LEWIS)

Environment - extremes

Impact of environment by tracing the progenitors of the most massive structures today. Relative role of “nature” and “nurture”.
Extremely underdense environments (voids) as regions where galaxy evolution driven only by internal processes.

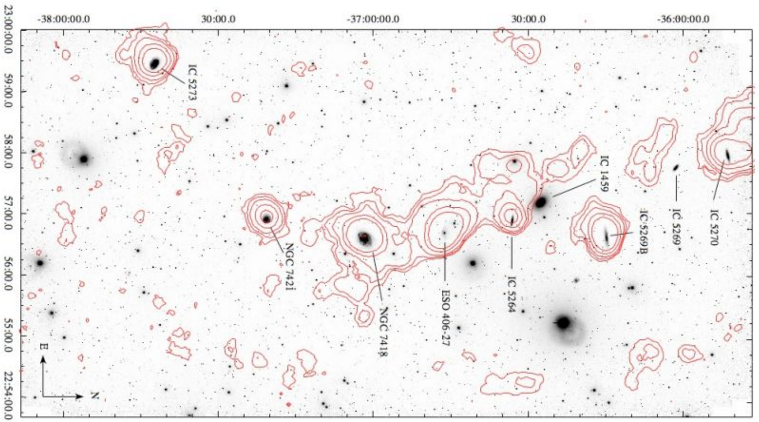


Esposito et al. 2025

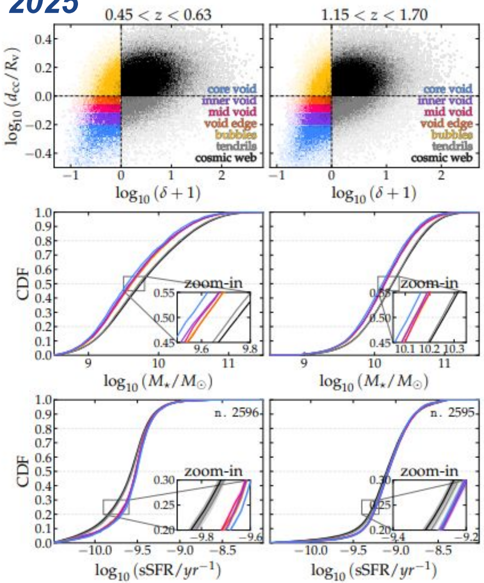


Cucciati et al.. 2018 (VUDS - Hyperion)

Iodice et al. 2020



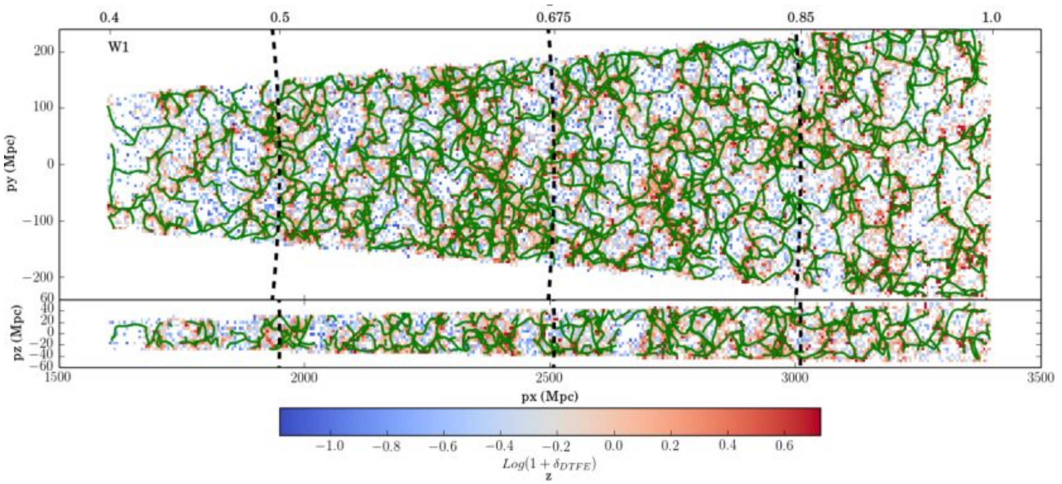
See talk by Tozzi & Molendi



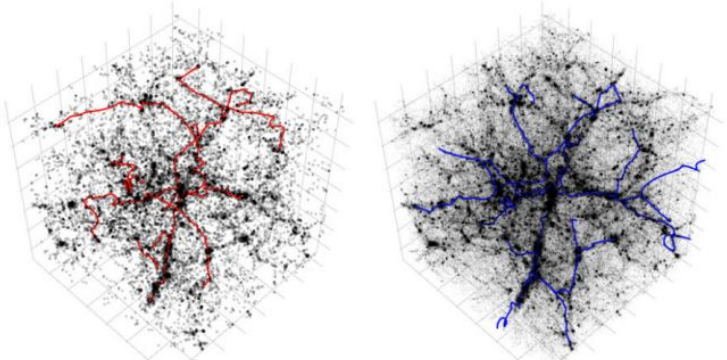
Papini et al. Euclid PLKP in prep

Environment - large scale structure

Malavasi et al. 2017 (VIPERS)

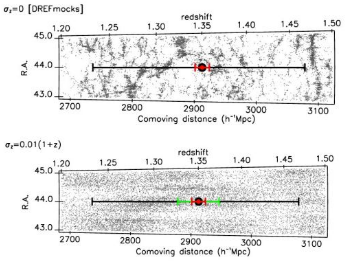


Characterization of large-scale structure in terms of walls, filaments, nodes requires good spectroscopic sampling (~>40-50%) or very good photometric redshift.



Zakharova et al. 2023

Increased activities on this subject in recent years, both on the observational side and on the theoretical side (heavy involvement in relevant Euclid WPs).

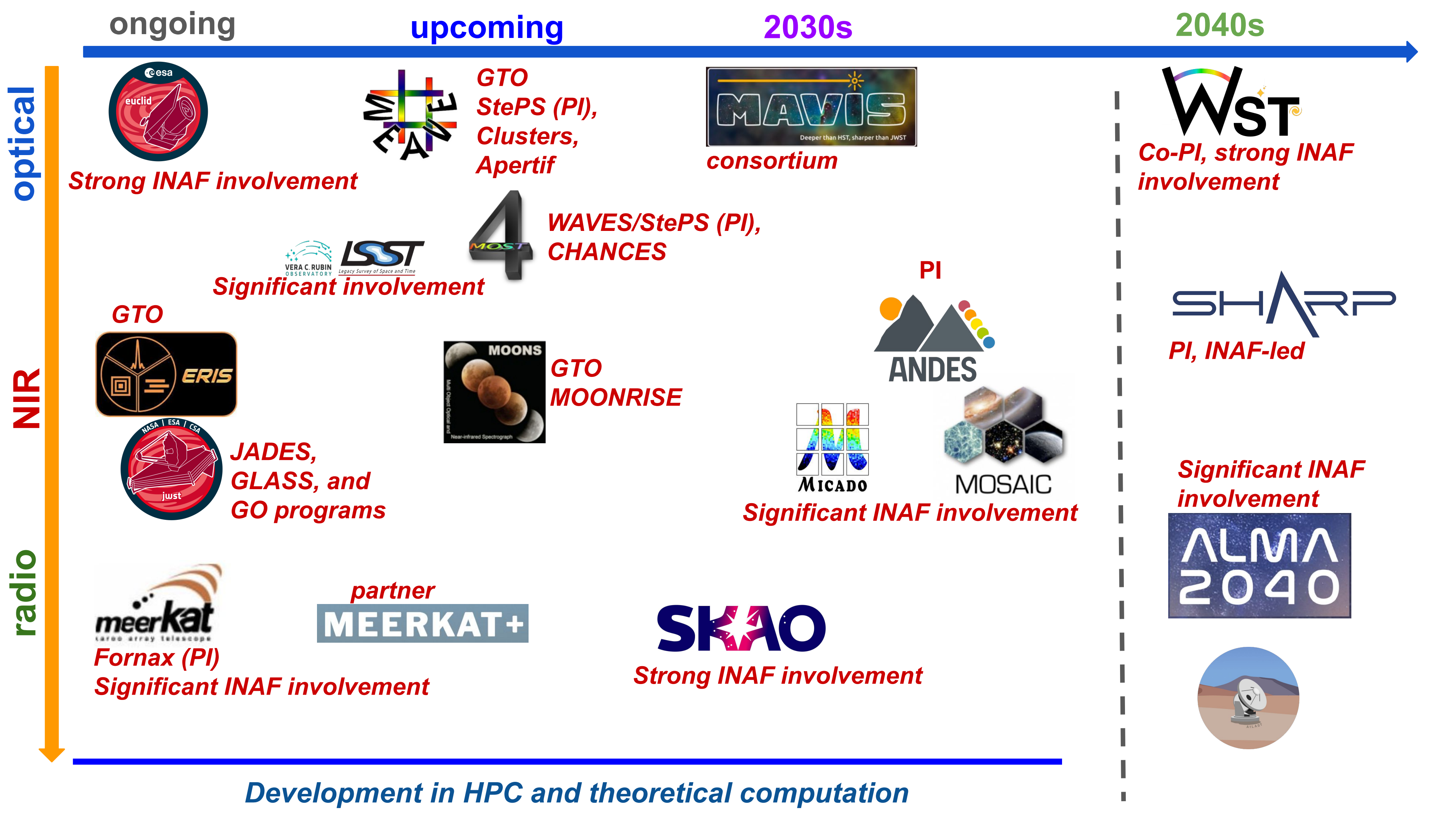


Cucciati et al. 2016

What do we need to make progress?

Multi-scale and multi-parameter problem that requires more and more a synergetic approach (wavelength, cosmic epochs, observations and theory)

- ➢ Robust **cosmic web characterization across redshift** (*highly complete and densely sampled spectroscopic redshifts; robust halo mass estimates*)
- ➢ Ability to reliably uncover the **stellar content and chemical properties** at increasing redshift, also using *new tools (e.g. machine learning)*
- ➢ **High spatial resolution** (< 1 kpc) morphological, kinematic and physical information of stars and gas to ***disentangle star formation and assembly histories***
- ➢ **Tailored interpretative tools**: cosmological simulations; chemical evolution models to physically interpret SFH-integrated properties and population trends across epochs
- ➢ **Connect galaxy demographics and physical properties across redshift** in a consistent way taking advantage of cosmological galaxy formation models
- ➢ **New tools for mining and exploiting large data volumes** (important both for observational data and theory products)


ongoing
upcoming
2030s
2040s
optical
NIR
radio
esa
euclid
Strong INAF involvement
GTO
StePS (PI),
Clusters,
Apertif
MAVIS
Deeper than HST, sharper than JWST
consortium
WST
Co-PI, strong INAF
involvement
VERA C. RUBIN OBSERVATORY
LSST
Legacy Survey of Space and Time
Significant involvement
4MOST
WAVES/StePS (PI),
CHANCES
PI
ANDES
SHARP
PI, INAF-led
GTO
ERIS
MOONS
Multi Object Optical and Near-infrared Spectrograph
GTO
MOONRISE
NASA | ESA | CSA
jwst
JADES,
GLASS, and
GO programs
MICADO
MOSAIC
Significant INAF involvement
Significant INAF
involvement
ALMA
2040
meerkat
karoo array telescope
Fornax (PI)
Significant INAF involvement
partner
MEERKAT+
SKAO
Strong INAF involvement
Development in HPC and theoretical computation

Criticalities and suggestions

General Recommendations from INAF Strategic Vision document (**2019**):

- **Support to Theoretical Astrophysics** …every participation to a new project/facility should involve a commensurate number of theorists … INAF should set up a specific program to support Theoretical Astrophysics - ***currently no dedicated channel***
- **Encourage coordination and creation of large groups** - …promote the coordination of researchers .. working in similar/homogeneous fields where our community plays an already established role internationally… requires an adequate and carefully tuned balance between long- and short-term projects - ***community still largely scattered, balance unsatisfactory***
- **Support "Basic Research" projects** - ***~regular calls but still not consolidated rules and an insufficient budget***
- **Foster interdisciplinary partnerships** - … promote and develop joint efforts aimed at enhancing interdisciplinary, convergent research .. both within INAF and with colleagues in other organizations - ***largely driven by individuals***
- **Improve the cooperation with ASI** - strict cooperation between INAF and ASI… INAF should be involved in all phases of the participation of its researchers to a space mission and take part in the approval process of a proposal … - ***tomorrow's discussion***
- **Give an effective role to the National Scientific Committees** - the action of the new committees has to be supported by all possible means, fostering a high-level scientific and technological debate and investing them with real programming and monitoring powers, taking advantage of the best practices of other institutions such as INFN - ***tomorrow's discussion***

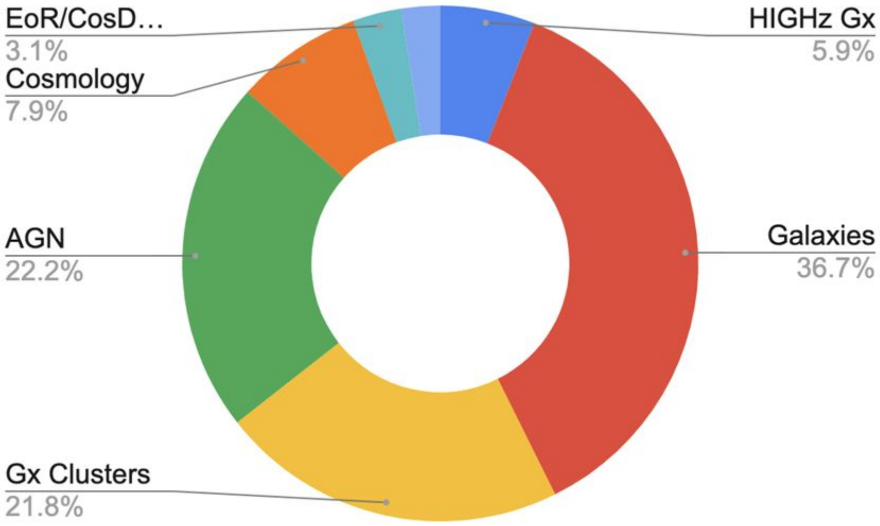
Criticalities and suggestions

Recommendations and considerations from CSN1 (24.01.2023)

- …general interest and appreciation for **tematic scientific meeting** (AGN, Clusters, GEE, …) - ***last GEE meeting in 2019***
- …actions (e.g. with presidents of other institutes or ministry) to **avoid defection of researchers who win significant EU funding towards Universities** (or abroad), and to increase general attractiveness of the institution at an international level - ***last 2 ERC in 2022 (both DR)***
- ….**impact of investments in large INAF infrastructures/big projects on research lines that are not linked directly to big projects,** but that constitutes fertile ground for the development of scientific cases and methodology also to support such project - ***still very much a criticality***
- … a unilateral (top-down) process, in which the **committees** are called to carry out different tasks, sometimes even burdensome in terms of commitment and time, but irrelevant for the community because they have **little impact on the decision-making flow of the institution** - ***tomorrow's discussion***
- Clear and concrete information about the **dialogues between the committees and the DS**… such dialogue … should be governed by specific regulations that have not been drafted yet - ***tomorrow's discussion***

Additional criticalities and suggestions

RSN1 FTE distribution @2022



Our personal view:

- ➢ The bulk of the scientific questions and research activities discussed in this review does not appear in the themes approved for the SN channel
- ➢ Wide and key involvement in large projects coexist with smaller groups with a very good international network of collaborators and visibility: *how to best support both routes?*
- ➢ Many researchers still have very limited access to PhD/Master students. ***Dedicated PhD fellowships*** to be supervised by INAF researchers
- ➢ International visibility and attractivity. ***Dedicated INAF post-doctoral fellowships***
- ➢ Dedicated ***INAF days*** in addition to or rather than separated RSN meetings to foster interdisciplinary collaborations.